Forbidden Ca II in the Sun

Unmasked by Way of Venus

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Abstract

Eleven high-dispersion spectra of Venus, taken with blue Doppler shifts have enabled us to unmask the 7323.88Å forbidden line of Ca II from terrestrial absorption. We obtain an equivalent width of 7.4 ± 0.4mÅ for this line in integrated sunlight. Our value of W_λ is smaller than previous values and much more accurate. The HSRA solar model gives a solar calcium abundance of $A_{Ca} = 6.21$.

I. Introduction

The forbidden line of Ca II at 7323.88Å has been the subject of interest in the last few years, as it is the most accessible line of [Ca II] in the solar spectrum. The subject has been discussed by Grevesse and Swings (1968), Lambert, Mallia, and Warner (1969), and Griffin and Griffin (1969). This line is difficult to measure because of a terrestrial H_2O line at 7323.972Å, which clobbers the [Ca II] line. Observers have exercised considerable ingenuity to get through, or around, this barrier. Grevesse and Swings used solar spectra obtained on the Jungfraujoch on a very dry day, to reduce the strength of the telluric line and bring out [Ca II] as a hump on its blue side. Lambert, Mallia, and Warner looked at the approaching (East) limb of the Sun and used the Doppler shift provided by solar rotation to expose the [Ca II] line as a hump in the blue wing of the telluric line (which was, of course, stronger at Oxford). Griffin and Griffin observed Arcturus, and, using the Doppler shift due to the Earth's orbital motion to avoid the H_2O line, detected and measured the 7323.88Å [Ca II] line. Then, working back through model atmospheres of Arcturus and the Sun, they inferred a value for the equivalent width of the solar [Ca II] line. These results all were in only fair agreement.

We ourselves have long used the Doppler shift due to orbital motion of the planets to uncover weak planetary H_2O lines normally masked by telluric lines. This shift can reach 1/3Å at 7200Å for Venus. On a dry day, at a mountain observatory, we felt that solar [Ca II] should be clearly visible in the spectrum of Venus. Such, indeed, was the case (see Fig. 1) Our results have been communicated privately to others before, but are published in full here.

II. Observations

Our spectra are listed in Table I. Plate numbers prefixed with "T" in the first column were taken with the coudé spectrograph of the 24-inch reflector at the Table Mountain Observatory of the Jet Propulsion Laboratory. The plate number prefixed with a "C" was obtained with the coudé spectrograph at the 82-inch Struve telescope at McDonald Observatory while plate numbers prefixed with an "N" were obtained with the McDonald 107-inch coudé spectrograph. The "EQ" entry is a spectrum scan taken with the 107-inch telescope coudé rapid scanner. All these spectra were taken as a part of our regular spectroscopic patrol of Venus CO_2 and H_2O regions. Young, et al. (1973), Young, et al. (1971), and Barker (1973) describe the 24-inch, the 82-inch and 107-inch photographic, and the 107-inch scanner set-ups respectively. All of the plates were taken at approximately 2 Å/mm. A 10-micron projected slit width was used for the 24- and 107-inch plates, while a 20-micron width was used for the 82-inch plate. These correspond to the resolution of the ammoniated IV-N plates used. The spectral scan was taken, in part, to see if there was any noticable difference between results obtained by two different methods. The slit was always oriented pole-to-pole on Venus through the area of maximum brightness.

Column 2 gives the dates of the observations, which were all made when Venus had an appreciable blue Doppler shift. Furthermore, we have used only specially selected plates taken on very dry days, when no more than a few mm of terrestrial water vapor were above the telescope. A useful rule of thumb was that the spectral region should at first glance be unidentifiable when compared to the Mount Wilson infrared solar spectrum. The rainy season at McDonald is summer, while that for California is winter, and the dates illustrate this fact.

Finally, spectra were selected which were taken close to the meridian transit of Venus. Figs. 1 and 2 show a representative spectrum with the [Ca II] line at 7323.88 well removed from the 7329.972 telluric line.

The third column of the Table gives the Doppler shift of Venus, in Ångstroms, from the tables of Niehaus and Petrie (1962). The last three columns give the equivalent widths of the [Ca II] line measured by the three authors.

III. Determination of the Equivalent Width

The plates listed in Table I were traced in the density mode with the recording microdensitometer at the Jet Propulsion Laboratory. The microdensitometer slit covered the central three quarters of the width of the spectrum in all cases. Projected slit widths of 10.9 and 21.8 microns were used. We did not prepare intensity tracings, for Young (1972) has shown that, for properly exposed, hypersensitized IV-N plates, a density tracing is equivalent to an intensity tracing, apart from a zero-point shift.

Equivalent width calibrations were based on the equivalent widths of four solar lines found in Moore, Minnaert, and Houtgast (1966): 7320.689 (72mÅ), 7326.160 (13mÅ), 7330.150 (17mÅ), and 7343.226 (20mÅ). The principal source of error was the measurement of the weak [Ca II] line. For example, when fourteen solar comparison lines were used to calibrate plate T 53, the resultant equivalent width was only 4.5 per cent lower than that obtained using only four solar lines.

Moore, Minnaert, and Houtgast give line intensities for the center of the solar disk, while our spectra of Venus show solar lines integrated over the disk. The difference can be up to 50 per cent for a given line. The scanner run was taken to check this point. It indicates that this source of error (again) is less than that introduced by the estimation of the area of the [Ca II] line itself.

The scanner data were processed as described by Barker (1973). In this case, the largest source of uncertainty was in estimating where the edges of the [Ca II] line reached the true solar continuum. At this resolution (about 275,000) the continuum is seldom flat for long, due to innumerable weak solar and terrestrial lines.

The last three columns of Table I list the estimates of the equivalent width (W_λ) by the three authors. For plates, the subscript "y" denotes estimates by one measurer for the best tracing of each plate, while the "s" column contains averages of two or more of the better tracings for each plate by another measurer. We give (formal) standard deviations for each plate measurer's average and for the average of the scan measures.

IV. As Figs. 1 and 2 show, 7323.88Å [Ca II] has been clearly observed. N487 is one of five "fair" spectra, in which the 7320.846 H_2O line is about as strong as the 7320.689 Fe I + Fe II line. On our six "good" spectra, all H_2O lines are weaker, and the [Ca II] line is well clear of the 7323.972 H_2O line. Because of the small number of measurements, and because of possible systematic errors involved (varying effects of the H_2O line wing, location of the continuum, etc.) it seems footless to do any elaborate statistical analysis. By weighing each scanner estimate three times as much as each plate estimate, we find $W_\lambda = 7.4 \pm 0.4$mÅ for the equivalent width of the 7323.88 [Ca II] line in integrated sunlight. The ±0.4 is not a statistical error estimate, but is our opinion of the uncertainty in our results which we feel is about 5%, because the systematic differences between plate and scanner values are of that size.

How does our result compare with earlier work? Grevesse and Swings estimated $W_\lambda = 7.0 \pm 0.4$mÅ for light from the center of the disk. Lambert, Mallia, and Warner predicted $W_\lambda = 8.3$mÅ at Cos $\theta = 1$ (center of the solar disk) and $W_\lambda = 12.0$mÅ at Cos $\Theta = 0.3$ (near the limb), and estimated $W_\lambda = 15 \pm 5$mÅ at Cos $\Theta = 0.3$ from their observations. Griffin and Griffin obtained an estimate of $W_\lambda = 11$mÅ from their indirect "Arcturus" method. In sum then, our value of W_λ is lower than previous values, and should be considerably more accurate.

In general, this lower value of W_λ lowers the derived solar calcium abundance. The particular value of A_{Ca} obtained depends on the solar model adopted. For example, Fig. 3 is a plot of W_λ vs A_{Ca} supplied to us by N. Grevesse, which uses the Harvard-Smithsonian Reference Atmosphere (Gingerich, et al., 1971); for $W_\lambda = 7.4$mÅ, we obtain $A_{Ca} = 6.21$.

V. Acknowledgement

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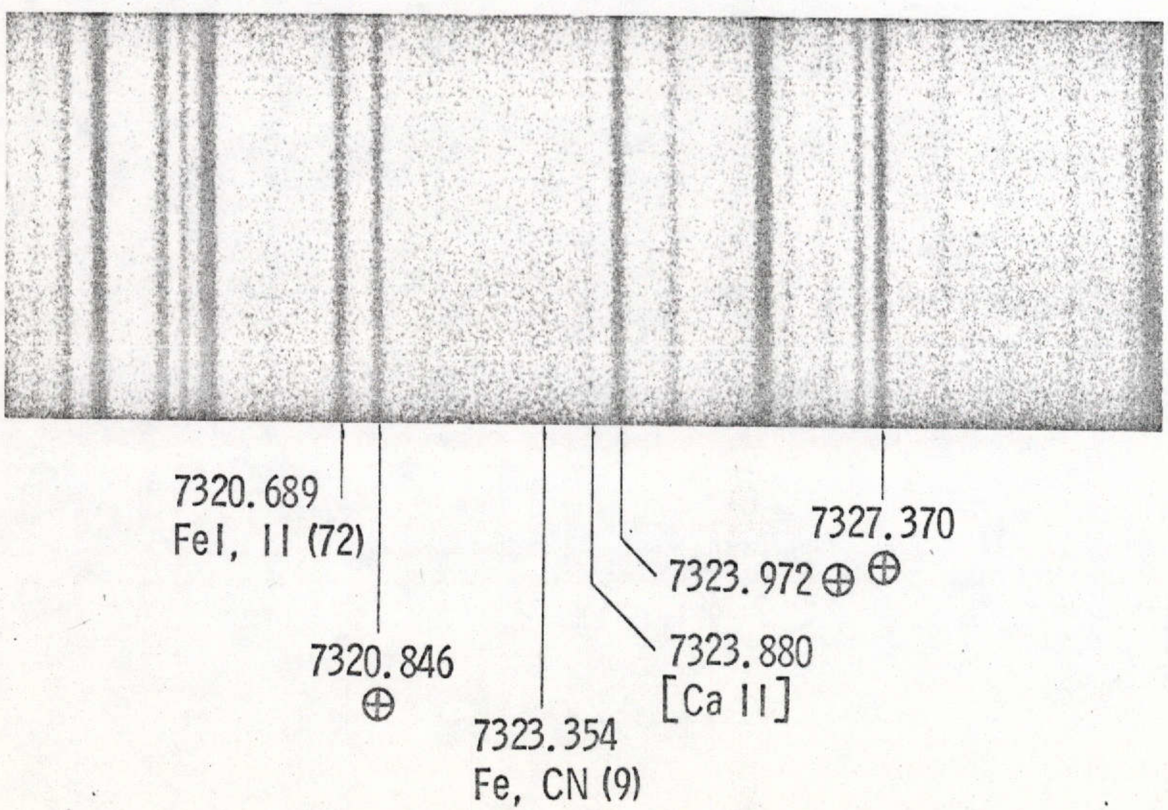
Table I

Observations of solar [Ca II]

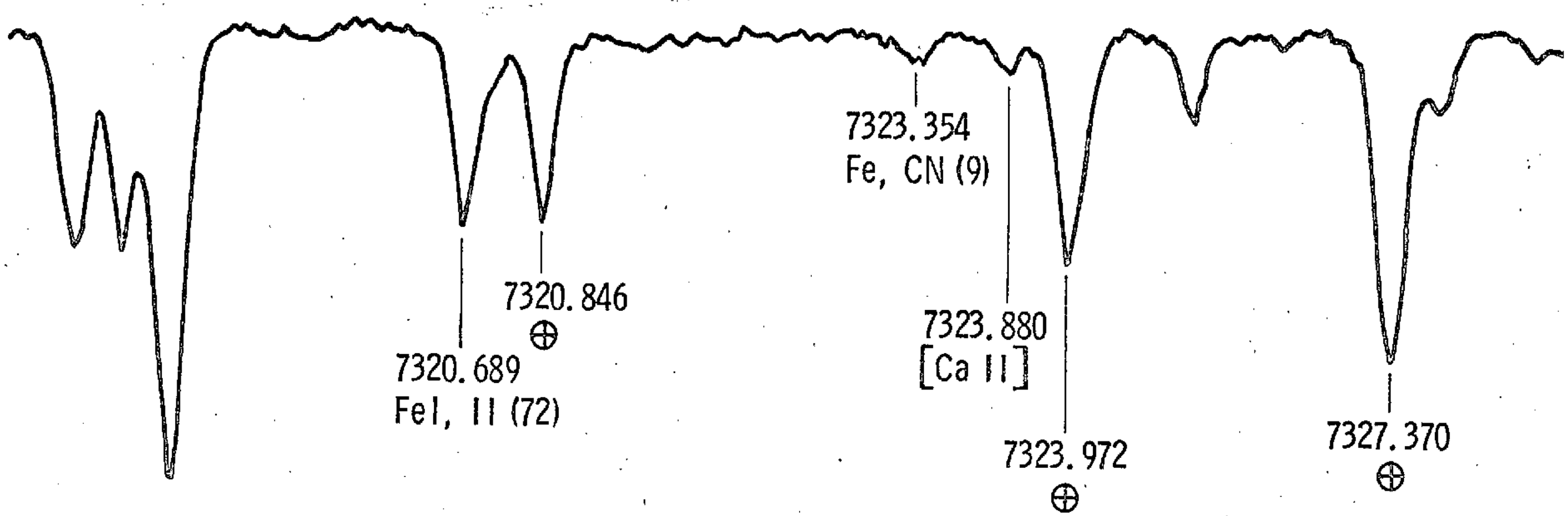
Plate	Date	$\Delta\lambda$(Å)	W_λ(mÅ)$_Y$	W_λ(mÅ)$_S$	W_λ(mÅ)$_B$
T 32	Apr. 14, 1970	-0.202	7.3	7.1	--
T 36	May 5, 1970	-0.193	12.9	9.0	--
C 6804	May 24, 1970	-0.233	10.1	6.9	--
T 53	Aug. 19, 1970	-0.331	6.2	6.6	--
T 56	Aug. 20, 1970	-0.331	7.0	6.7	--
T 57	Aug. 21, 1970	-0.331	7.7	7.5	--
T 62	Aug. 25, 1970	-0.331	5.3	6.8	--
N 487	Oct. 6, 1970	-0.283	7.7	7.3	--
N 489	Oct. 7, 1970	-0.280	6.6	7.3	--
Averages of plate measures			7.7 ± 0.7	7.4 ± 0.3	
EQ 4977	Dec. 11, 1973	-0.294	6.7	7.1	7.1
Average of scan measures			7.0 ± 0.1		

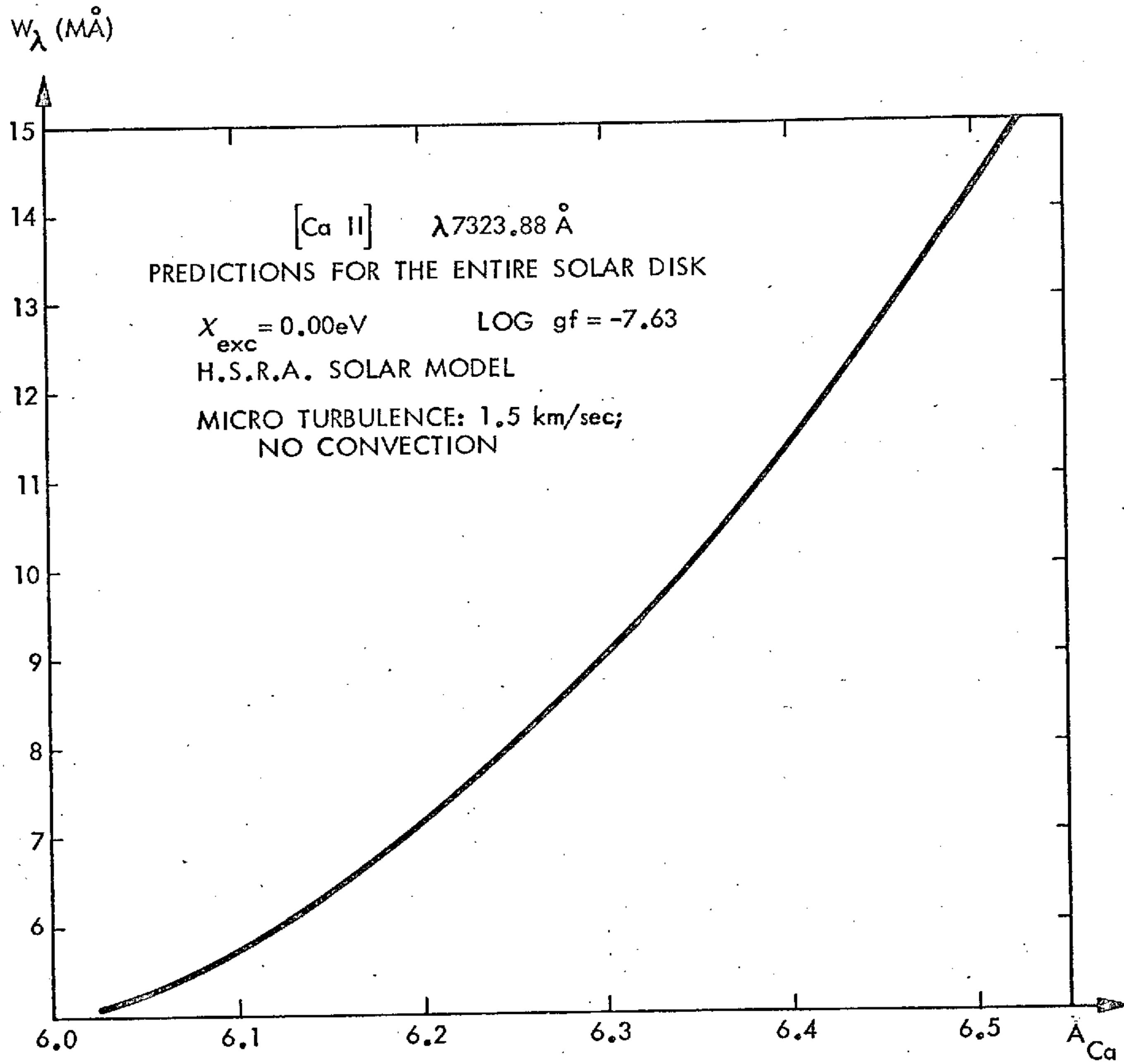
List of Figures

[Ca II] N487


7320.689
FeI, II (72)
7320.846
⊕
7323.354
Fe, CN (9)
7323.880
[Ca II]
7323.972 ⊕
7327.370
⊕

[Ca II] N487


7320.846
⊕
7320.689
FeI, II (72)
7323.354
Fe, CN (9)
7323.880
[Ca II]
7323.972
⊕
7327.370
⊕


W_λ (MÅ)
15
14
13
12
11
10
9
8
7
6
6.0
6.1
6.2
6.3
6.4
6.5
A_{Ca}
[Ca II] λ7323.88 Å
PREDICTIONS FOR THE ENTIRE SOLAR DISK
χ_{exc} = 0.00eV LOG gf = -7.63
H.S.R.A. SOLAR MODEL
MICRO TURBULENCE: 1.5 km/sec;
NO CONVECTION